Jet Propulsion Laboratory
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Navigating MarCO, the First Interplanetary CubeSats

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27th International Symposium on Space Flight Dynamics
18th Australian International Aerospace Congress
Melbourne, Australia, 24-26 February 2019

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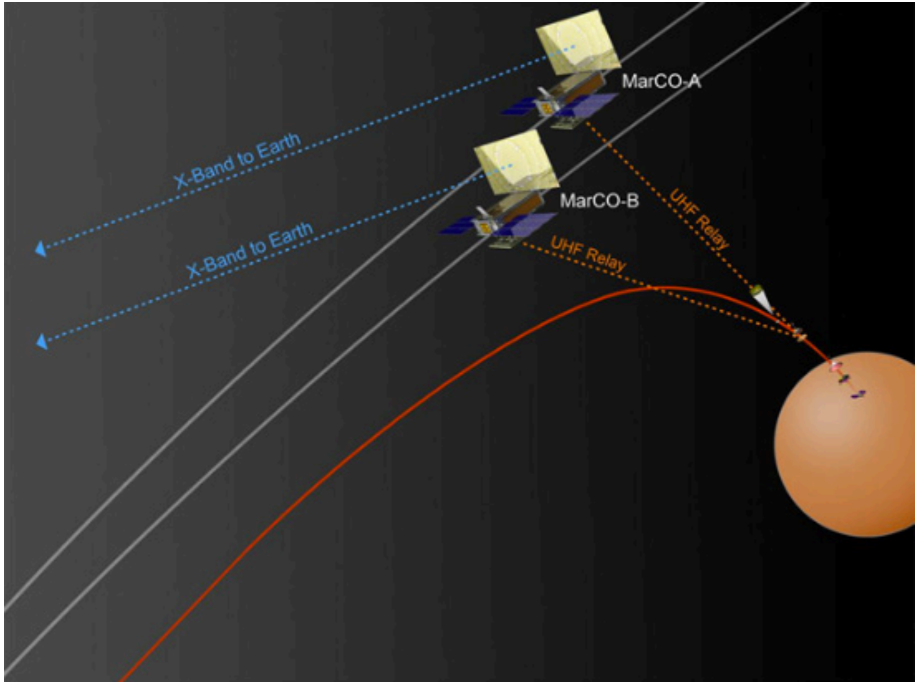
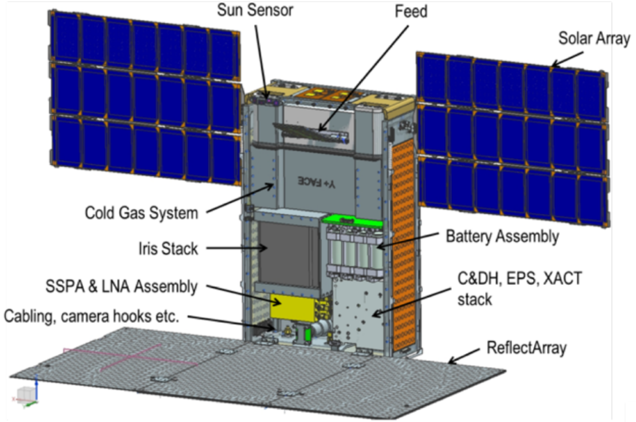
MarCO Mission Overview

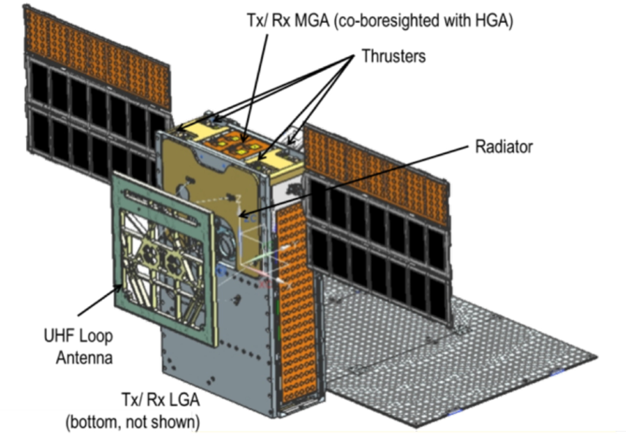
- The NASA's MarCO probes were proposed in 2014 as a technology demonstrator for deep-space CubeSats.
- They were to be launched together with NASA's InSight and fly by themselves to Mars.
- They were to perform data relay of the InSight lander as it descended into Mars.
- First users of the new, small, deep-space IRIS radio.



Probe Configuration

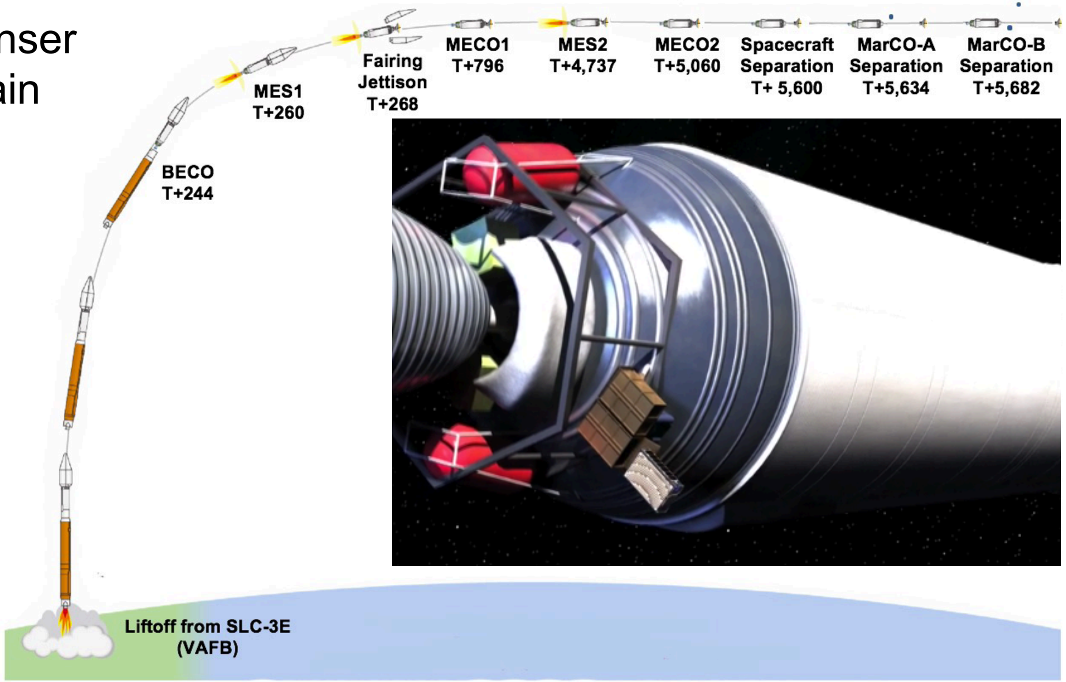
- Two 6U CubeSats, ~14 kg each
- JPL-developed telecom system: IRIS radio, X-band patch antennas, flat-pack HGA reflector, and UHF antenna
- Blue Canyon Technologies' XACT attitude control system with 3 reaction wheels and 1 star tracker
- Cold-gas thruster system (40 sec I_{sp}, total ~60 m/sec) provided by VACCO
  - 4 axial thrusters for trajectory control
  - 4 60° canted thrusters for attitude control (unbalanced)





MarCO Release

- The MarCO CubeSats were mounted using a Tyvak NLAS dispenser located at the Centaur’s aft bulkhead carrier.
  - They were switched off before being integrated into the dispenser and were only switched on again on release.



- The probes were released after InSight separated.

Key Navigation Requirements

- Do no harm
  - Don't endanger InSight or the launch vehicle
  - Don't come close to InSight
  - Don't contaminate InSight
  - Comply with Mars Planetary Protection requirements
- Demonstrate CubeSat technologies
  - Deep space operation of a CubeSat
  - X-band communication at 8kbps downlink at 1 AU
  - Deep space trajectory correction maneuvers to target the Mars flyby
- Provide bent-pipe relay for InSight entry, descent, and landing
  - Convert InSight's UHF stream to X-band and retransmit it to the Earth

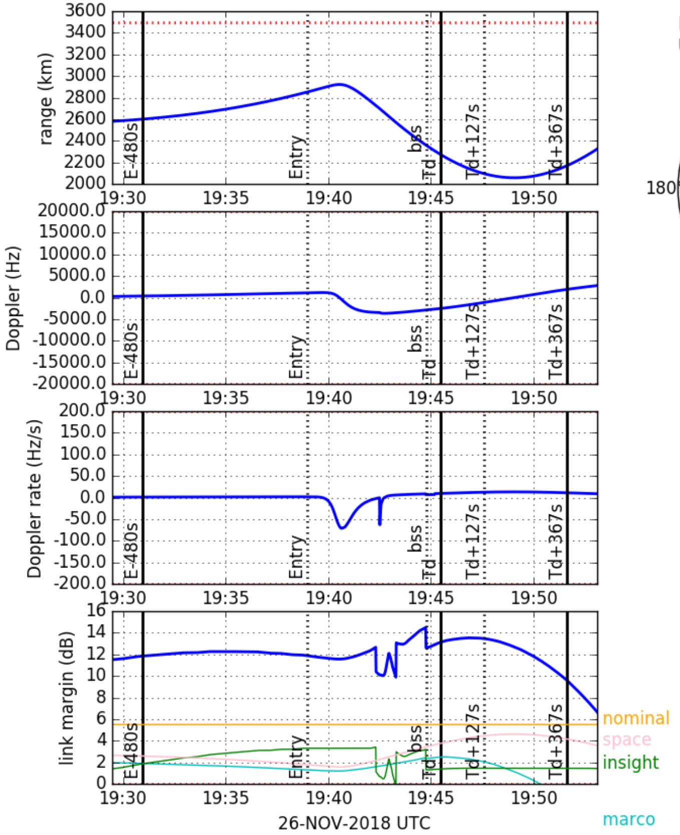
Do No Harm

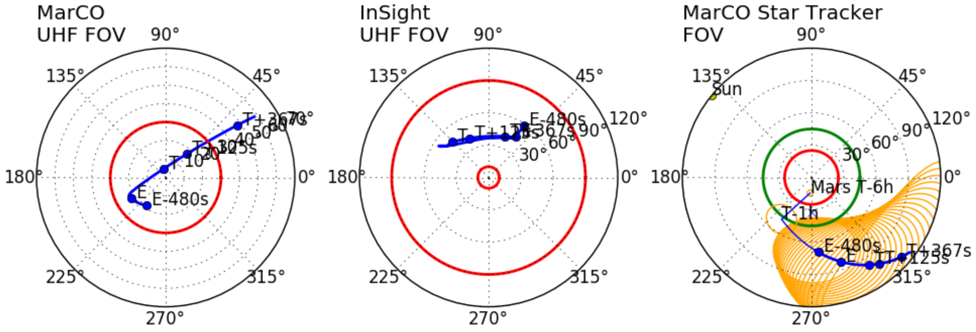
- The propulsion system used an inert cold gas propellant in order to avoid danger or contamination of InSight or the launch vehicle.
- The 1.5 m/s separation delta-V pushed the MarCOs away from InSight. MarCO's maneuvers were designed so the probes did not get too close (less than 1000 km) to InSight.
- Maneuvers were only executed after sufficient separation was achieved, in order to avoid cross-contamination.
- Initially we tried trajectory-based Planetary Protection compliance, but it would have imposed significant constraints on the InSight launch opportunities, so it was decided to combine this analysis with vehicle break-up and burn-up analysis of a possible Mars entry in order to cover all cases.

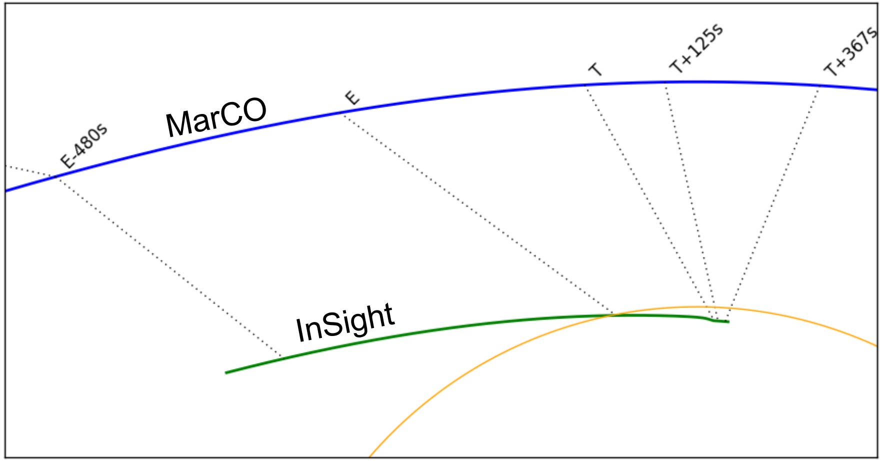
Flyby Trajectory Optimization

- The design of the flyby trajectory had as goal to maximize UHF link margin while:
  - Pointing MarCO's high-gain antenna to the Earth
  - Keeping InSight in view of the MarCO's UHF antenna
  - Keeping MarCO in view of the InSight UHF wrap-around antenna
  - Allowing for adequate link margin from the start of the UHF transmission at entry minus 8 minutes to landing plus 5 minutes.
- MarCO's antennas were fixed so an attitude was selected with the high-gain antenna pointed to the Earth and the UHF antenna pointed towards the InSight landing site.
- The InSight wrap-around UHF antenna pattern had areas with reduced gain that had to be avoided.
  - It was possible to fly either left or right of InSight, but not directly over it.

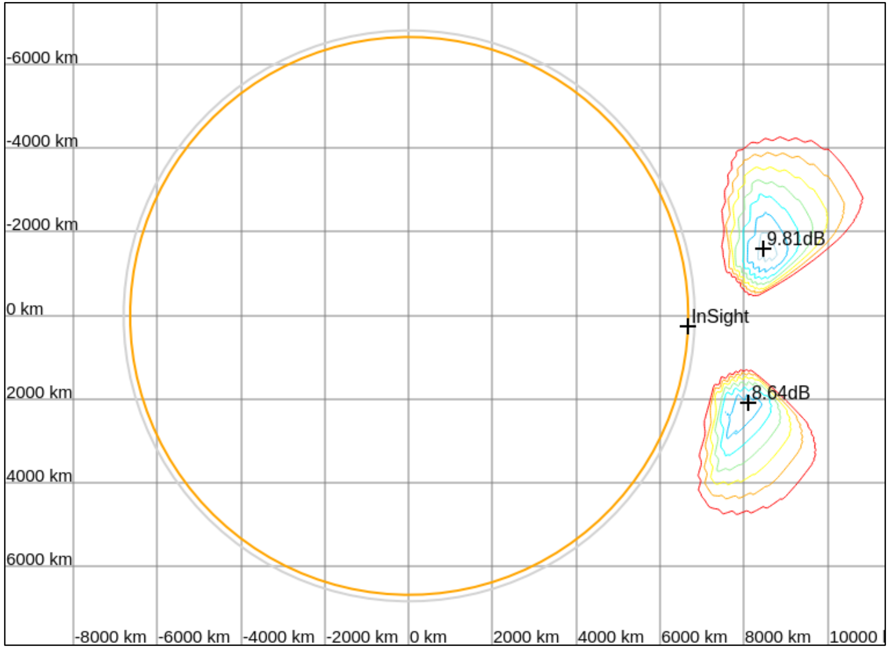
Flyby Trajectory Optimization



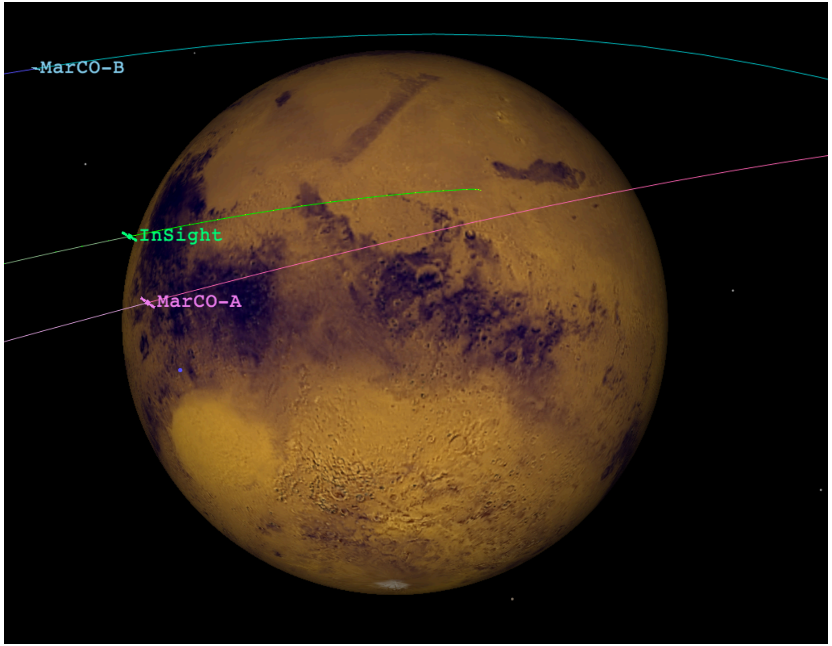




Flyby Trajectories and Targets



Mars B-plane



Trajectory Correction Maneuvers (TCMs)

- The propulsion system had not been extensively tested before launch and maneuver execution performance was highly uncertain.
- We had a number of issues during flight with the propulsion system and were forced to perform additional calibrations and to split trajectory maneuvers into segments.
- Internal leaks developed in both probes. and also an external leak on MarCO-B, making trajectory determination and correction difficult.

Activity	MarCO-A		MarCO-B	
	Planned	Actual	Planned	Actual
TCM calibrations	May 8	May 8-13 Aug. 15-Sep. 21	May 9	May 15-21
TCM-1	May 20	May 22-Jun. 2	May 22	May 31
TCM-2	Aug. 10	Jul. 30-Aug. 13	Aug. 13	Aug 15-17
TCM-3	Oct. 24	Sep. 26-Oct. 3	Oct. 26	Sep. 25-Oct. 30
TCM-4	Nov. 15	Not needed	Nov. 16	Nov. 16
TCM-5	Nov. 23	Not needed	Nov. 24	Not needed

Effect of the Propellant Leaks

- The internal leak between the propellant tank and the plenum equalized the pressure between the two and allowed for liquid to accumulate in the plenum.
- The external leak in one of the attitude control thrusters for MarCO-B generated a torque and an acceleration.
- In order to mitigate the effect of the leak, the probe was put into a spin with the solar panels pointing to the Sun, and thruster valves were open periodically to blowdown the plenum and reduce its pressure.
- Actuating the tank-to-plenum valve for trajectory or attitude maneuvers resulted into varying leak levels. If the leak was strong, the angular momentum would grow fast and multiple angular momentum reduction burns would be automatically executed in succession.
- The tank-to-plenum leaks made maneuver execution performance unpredictable.

Trajectory Determination: Tracking Schedule

From	To	Doppler/Range Passes	ΔDOR Sessions
Launch	Launch + 30 days	Daily	None
Launch + 30 days	Flyby – 28 days	3 per week	1 per week
Flyby – 28 days	Flyby – 14 days	5 per week	4 per week
Flyby – 14 days	Flyby	Daily	4 per week

- Due to energy and thermal limitations, typical Doppler/range tracking pass duration was only about one hour, with range was performed just for part of the pass for about every other pass.

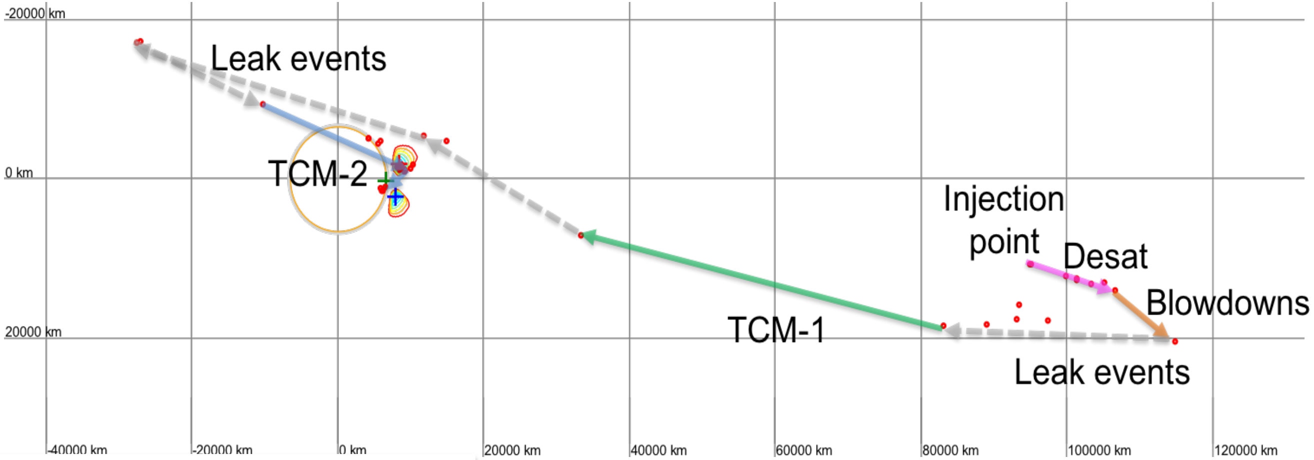
Trajectory Determination Challenges

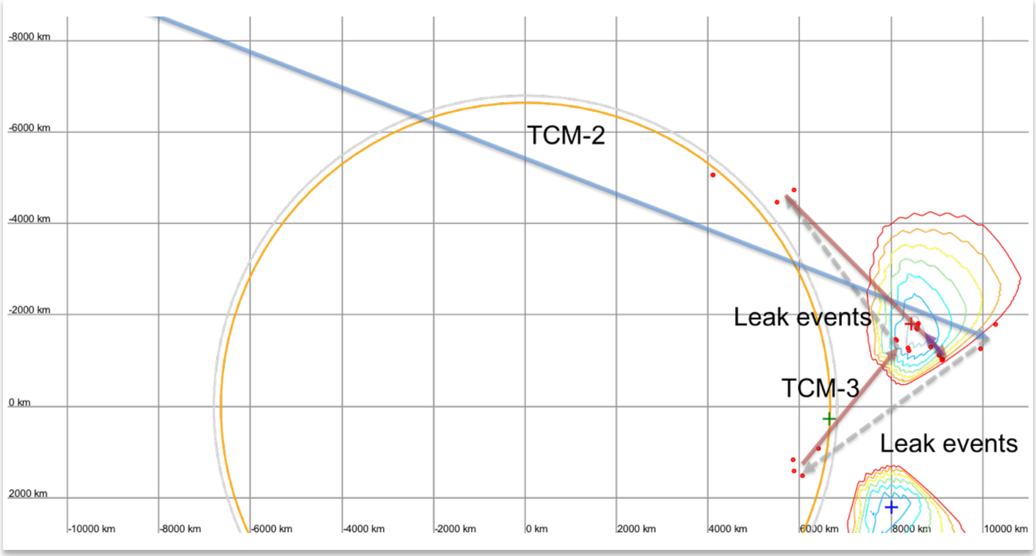
- New IRIS radio with range and Doppler biases

- Shorter pass duration and fewer passes than other Mars missions.

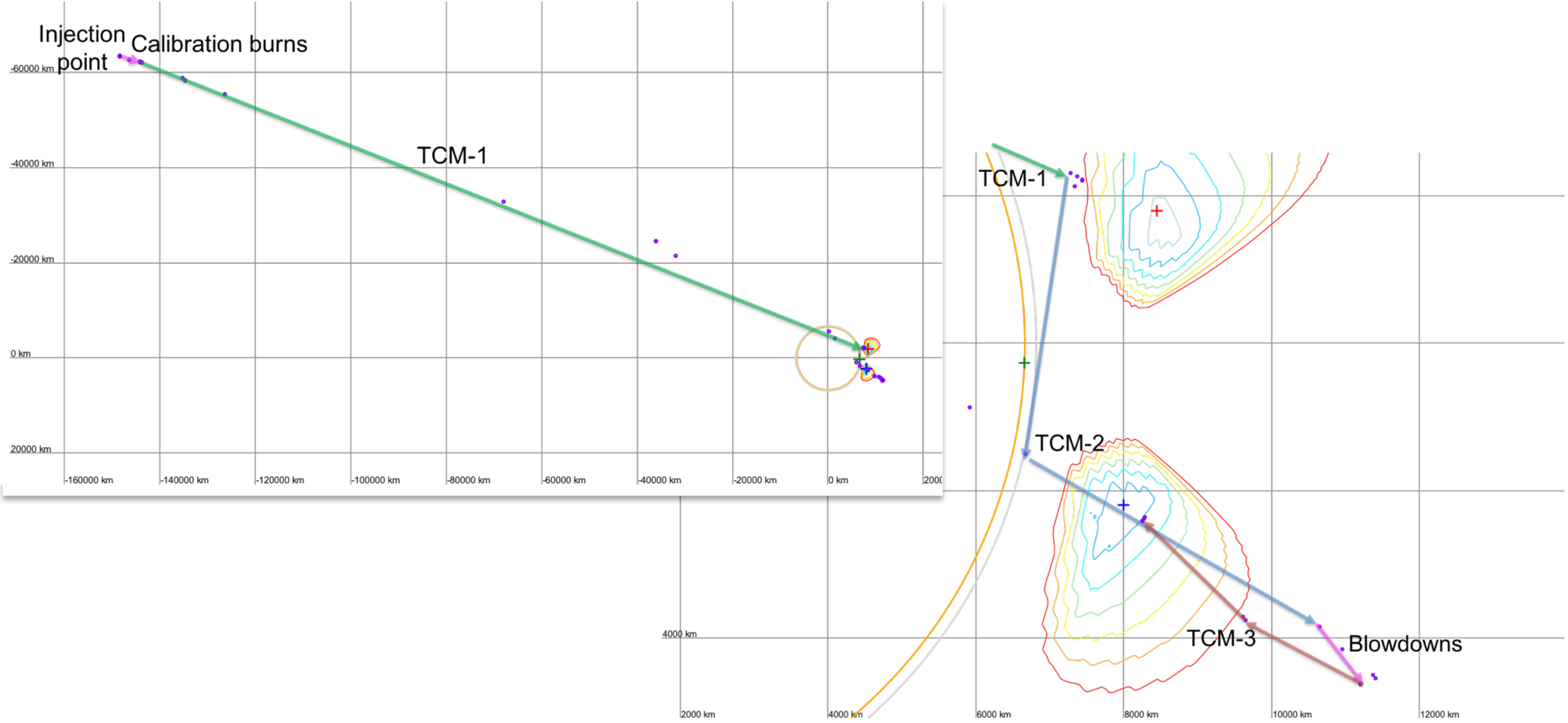
- Modeling of the propulsion system leak and related mitigation actions.
  - With the blowdowns and the accelerations due to the leak, with had more unknowns than observables when just using tracking data.
  - Attitude and propulsion system telemetry was used to obtain a better initial estimate of the effect of plenum blowdowns on the trajectory.

Path To Mars: MarCO-B

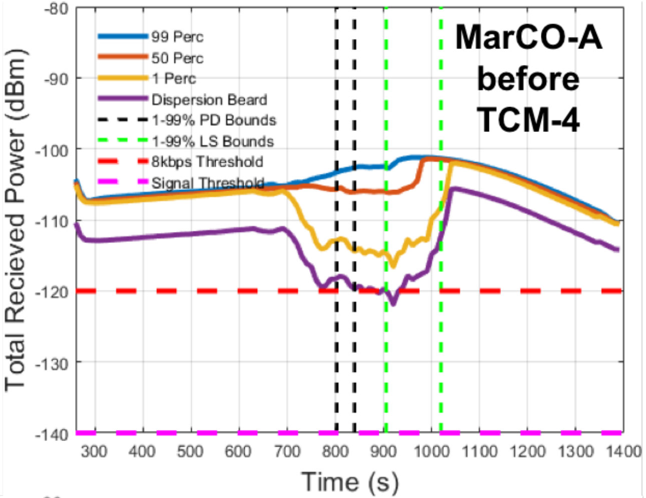


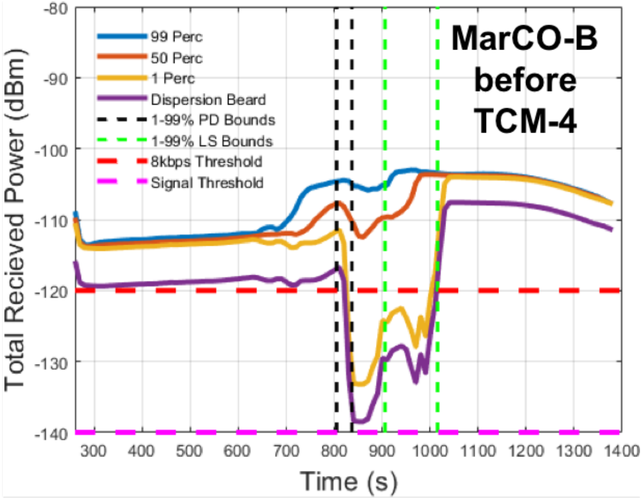


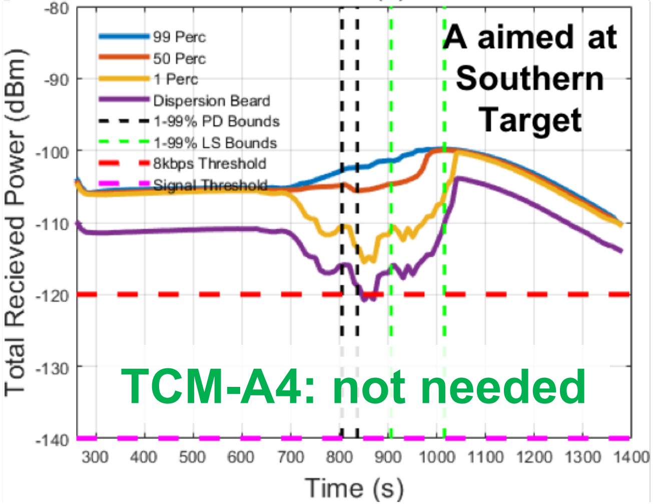
Path To Mars: MarCO-A

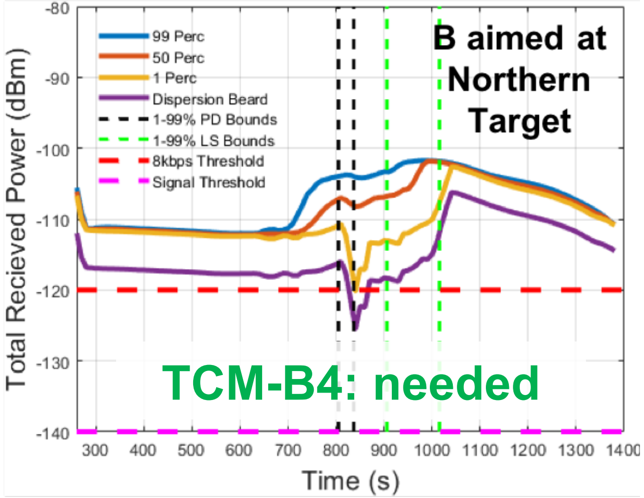


TCM-4 Decision



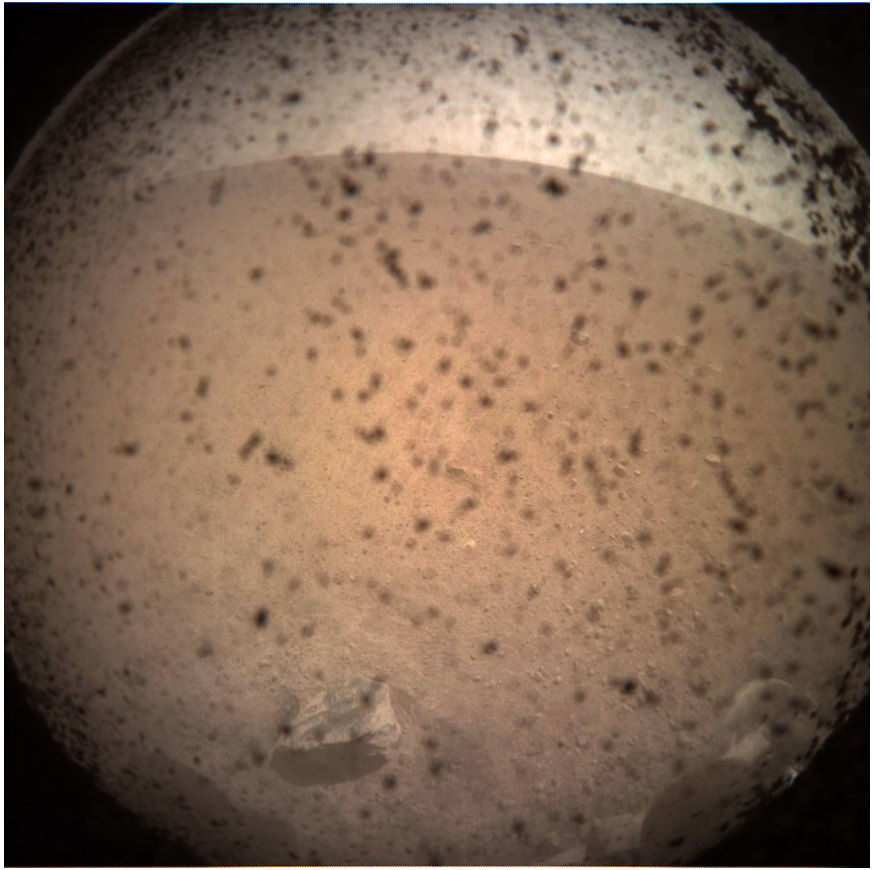






Flyby Performance

- Both MarCOs were able to make it to Mars alive.
- The MarCOs transmitted InSight's UHF telemetry during entry, descent, and landing in near real-time, including the first image taken by InSight after landing.
- We showed that CubeSats can be operated in deep space.



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